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A QUASI-SINGLE MODE OPTICAL FIBER FOR LONG-HAUL TRANSMISSION IN SEVERE BENDING ENVIRONMENTS

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We investigated the feasibility of a quasi-single mode optical fiber for low bending losses in long-haul transmission at 1550 nm. The advantage of a quasi-single mode fiber is that for comparable bending losses the relative index difference, Δ , can be smaller than the Δ in a single-mode fiber. We demonstrated that a quasi-single mode fiber with $\Delta = 0.72\%$ and single-mode cutoff wavelength, λ_c , equal to 1630 nm exhibits bending losses as low as the losses in a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm. Modal noise and modal dispersion effects in the quasi-single mode fiber also were tested and found to be minimal. This paper describes the matched-clad, quasi-single mode fiber and presents the test results.

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2 May 1994

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Encl: (1) "A Quasi-Single Mode Optical Fiber ..."
(2) Code 961 memo

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2. The work reported in Encl. (1) was performed while I was a member of Code 534. It was supported by the Center's IED program in FY90, and by the Office of Advanced Technology in FY91. A U.S. Patent (Ref. (a)) was issued on 11 April for the invention described in Encl. (1).

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A Quasi-single Mode Optical Fiber for Long-Haul Transmission in Severe Bending Environments

Neil Kamikawa, *Member, IEEE*, and Ching-Ten Chang, *Member, IEEE*

Abstract—We investigated the feasibility of a quasi-single mode optical fiber for low bending losses in long-haul transmission at 1550 nm. The advantage of a quasi-single mode fiber is that for comparable bending losses the relative index difference, Δ , can be smaller than the Δ in a single-mode fiber. We demonstrated that a quasi-single mode fiber with $\Delta = 0.72\%$ and single-mode cutoff wavelength, λ_c , equal to 1630 nm exhibits bending losses as low as the losses in a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm. Modal noise and modal dispersion effects in the quasi-single mode fiber also were tested and found to be minimal. This letter describes the matched-clad, quasi-single mode fiber and presents the test results.

I. INTRODUCTION

WE INVESTIGATED techniques to reduce both bending losses and spectral attenuation in an optical fiber to increase transmission distances at 1550 nm in applications where the fiber is severely bent with bending radii of several mm. Our approach is to combine a pure-silica core fiber for spectral attenuation reduction with quasi-single mode operation for bending loss reduction. We achieved an intermediate goal in which a quasi-single mode fiber was realized in a matched-clad design to study bending loss, modal noise, and modal dispersion. The matched-clad, quasi-single mode fiber with $\Delta = 0.72\%$ and $\lambda_c = 1630$ nm exhibits low bending losses that are comparable to a single-mode fiber with $\Delta = 0.93\%$ and $\lambda_c = 1259$ nm, but the smaller Δ in the quasi-single mode fiber permits the future fabrication of the quasi-single mode specification in a depressed-clad, pure-silica core design. The largest Δ reported in a pure-silica core fiber is 0.73% [1].

The high λ_c in the quasi-single mode fiber has the same effect in reducing bending losses as the high Δ in the single-mode fiber. This is demonstrated in bending tests and is in agreement with measured guided-wave phase indexes and refractive-index profiles. With λ_c of 1630 nm $>$ 1550 nm, both the LP_{01} and LP_{11} modes may propagate and may penalize the transmission link via modal noise and multimode modal dispersion. We found that at 200 MB/sec the modal noise penalty is ≤ 0.3 dB, and determined that there is no modal dispersion since the spectral attenuation of the LP_{11} mode is about three orders of magnitude greater than the attenuation of the LP_{01} mode at 1550 nm. The small modal effects also are consistent with our guided-wave phase-index measurements

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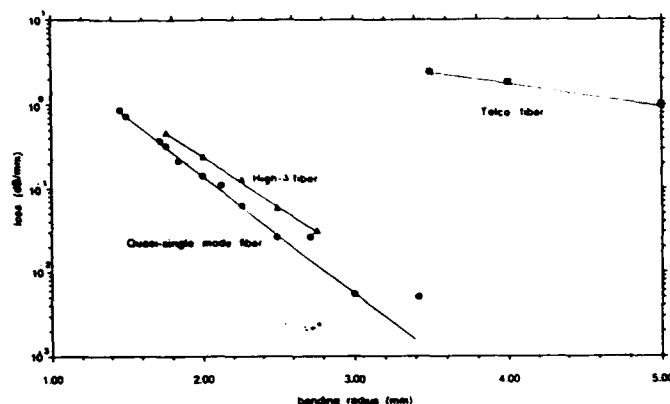


Fig. 1. Measured bending losses at 1550 nm.

which show that mode coupling is small and that the LP_{11} mode is barely guided.

This letter describes the matched-clad, quasi-single mode fiber and discusses the results of bending, guided-wave phase-index, modal noise, and spectral attenuation tests.

II. FIBER DESCRIPTION

The performance goal for the matched-clad, quasi-single mode fiber was to achieve very low bending losses similar to bending losses in a high- Δ , single-mode fiber [2], [3] described in Table I. Further, the quasi-single mode fiber should have a $\Delta \leq 0.73\%$, the largest Δ reported for a pure-silica core fiber [1], to allow future implementation of the fiber in a pure-silica core design. The quasi-single mode fiber described in Table I meets these requirements. The fiber's measured bending losses are nearly equal to that in the high- Δ fiber, as shown in Fig. 1, and its Δ is 0.72%.

The nearly equal bending losses can be explained using a single-mode step-index model with core radius, a , core index, n_1 , and cladding index, n_2 . The propagation constant of the guided optical wave is constrained by $n_2 k \leq n k \leq n_1 k$, where $k = 2\pi/\lambda$, the free-space propagation constant, and n is the guided-wave phase index. In a bend of radius R , the LP_{01} mode field amplitude-loss coefficient, α , in Nepers/mm is given in [4] and its corresponding optical power-loss coefficient $\alpha_c (= 8.68\alpha)$ in dB/mm is

$$\alpha_c = \frac{8.68}{4} \sqrt{\frac{\pi k}{R}} \frac{(n_1^2 - n^2) \exp[-2(n^2 - n_2^2)^{3/2} k R / 3n^2]}{(n^2 - n_2^2)^{3/2} (ka \sqrt{n_1^2 - n_2^2})^2 K_1^2(ka \sqrt{n^2 - n_2^2})} \quad (1)$$

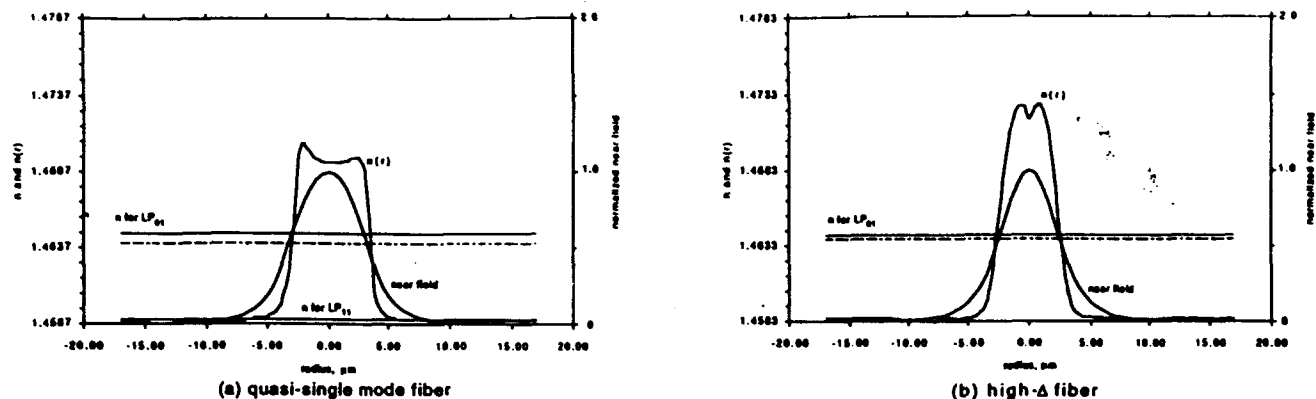


Fig. 2. Refractive-index profile $n(r)$, near field, and calculated (solid horizontal line) and measured (dashed horizontal line) phase index n at 1550 nm. (a) quasi-single mode fiber. (b) high- Δ fiber.

TABLE I
FIBER SPECIFICATIONS

Fiber	λ_c	n_1	n_2	Δ	ω_∞	ω_0	n for LP_{01} (measured)	n for LP_{01} (calculated)	n for LP_{11} (measured)
	nm			%	μm	μm			
Quasi-single mode	1630	1.4692	1.4587	0.72	3.97	3.96	1.4640	1.4646	1.4590
High Δ	1259	1.4721	1.4585	0.93	4.01	3.53	1.4637	1.4640	
Telco	1154	1.4635	01.4585	0.36	6.40	5.39	1.4605	1.4602	

λ_c is the cutoff wavelength, n_1 is the core index, n_2 is the cladding index, Δ equals $(n_1 - n_2)/n_2$, ω_∞ is the cladding-field decay constant, ω_0 is the rms mode-field radius, and n is the guided-wave phase index.

where K_1 is the modified Hankel function of first order. The guided-wave phase index, n , in (1) can be obtained by solving the characteristic equation [5], [6] or by measuring the near and far fields [7]. According to (1), the theoretical bending losses in both the quasi-single mode fiber and high- Δ fiber are about 1.5 dB/mm for a 2-mm radius bend.

III. TEST RESULTS AND DISCUSSION

As shown in Fig. 1, the measured bending losses in the quasi-single mode fiber at 1550 nm are comparable to losses in the high- Δ fiber and are much less than losses in a typical telco fiber that was tested for comparison. The measured loss in the quasi-single mode fiber at $R = 2.0$ mm is 0.15 dB/mm but (1) predicts a loss of 1.5 dB/mm, assuming a step-index profile. The lower measured loss can be explained by the non-step refractive index profile with the small central index depression [8], as shown in Fig. 2. Small radius bends cause the peak of the near field to shift outward from the central index depression toward the off-center index maximum at the core-clad interface. The off-center index maximum reduces the degradation of the mode confinement caused by the bend, which reduces the bending loss to less than that predicted by (1).

For a given R and k , the LP_{01} mode bending loss is mainly determined by the exponential term and the Hankel function term in (1). These two terms in turn depend on $n^2 - n_2^2$ which is proportional to $n - n_2$ for the weakly-guided fibers in Table I. A larger $n - n_2$ indicates stronger optical confinement and reduces bending losses. Our experimentally derived $n - n_2$

values are approximately the same for the quasi-single mode fiber and the high- Δ fiber. The strong optical confinement in the former fiber is due to longer λ_c (or larger core diameter) as shown in Fig. 2(a), while the strong optical confinement in the latter fiber is due to the large Δ as shown in Fig. 2(b).

Our estimations of n are believed to be reliable since measured and calculated n are nearly the same in each fiber, as shown in Fig. 2 and Table I. The measured n is based upon the near-field measurement to estimate the LP_{01} mode phase index as $n \approx \left(\frac{2}{k^2 n_2 \omega_\infty^2} \right) + n_2$. Here, Petermann's cladding-field decay constant, ω_∞ [7], is obtained by fitting the expression $E(r) \propto \left(\frac{1}{\sqrt{r}} \right) \exp \left(\frac{-2r}{\omega_\infty} \right)$ to the measured near field in the cladding. The near fields were obtained by taking the inverse Hankel transformation of the far fields measured at 1550 nm. Fig. 3 shows the measured and fitted near fields. The calculated n is based upon the expression $n = \sqrt{b(n_1^2 - n_2^2) + n_2^2}$, where b is the normalized propagation constant. By measuring λ_c , the normalized frequency $V = 2.405 \left(\frac{\lambda_c}{\lambda} \right)$ is estimated and used to obtain b by solving the LP_{01} mode characteristic equation [5], [6].

The λ_c were measured using the multimode reference technique and the refractive indexes were measured with the refractive near-field method. The root-mean-square mode-field radii, ω_0 , also were measured as shown in Table I. It is interesting to note that the high- Δ fiber exhibits a smaller ω_0 but the bending losses in the both fibers are similar, suggesting that ω_0 is not a good predictor of bending losses in fibers of dissimilar refractive-index profiles.

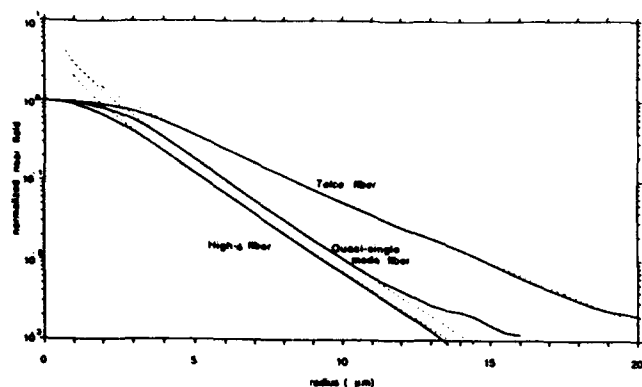


Fig. 3. Measured near fields at 1550 nm (solid line) and curve fit to near field in cladding (dashed line).

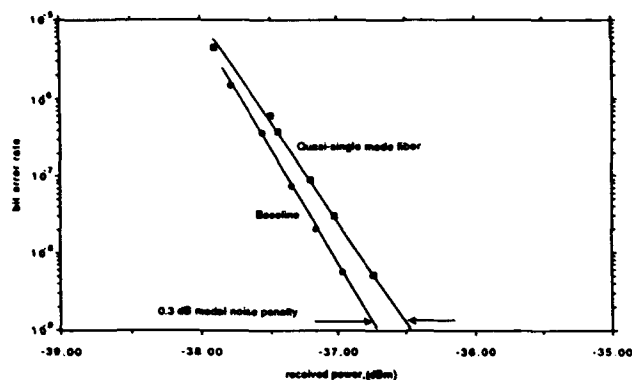


Fig. 4. Bit-error rate measured at 200Mb/s.

Since the quasi-single mode fiber supports both the LP_{01} and second-order LP_{11} modes modal noise and modal dispersion can impact system performance. To determine the impact of modal noise bit-error rates were measured on a 2.1-km length of the quasi-single mode fiber at a data rate of 200 Mb/s and a pseudo-random bit sequence length of $2^{20} - 1$. A misaligned splice characterized by a 1.5-dB loss was inserted 2 meters from the end of the fiber that was terminated in a connector and attached to a pigtailed PINFET receiver to create a worse-case situation for modal noise. However, the modal noise power penalty was only about 0.3 dB, as shown in Fig. 4, with respect to a baseline measurement made by removing the quasi-single mode fiber and connecting the laser transmitter pigtail directly to the PINFET receiver pigtail. The large difference between the n for the LP_{01} mode and the n for LP_{11} mode in the quasi-single mode fiber indicates that mode coupling is small and supports the low modal noise penalty test result.

The spectral attenuation of the modes at 1550 nm were measured using a cutback technique [9] to indirectly evaluate modal dispersion since long lengths of the quasi-single mode fiber were not available for direct dispersion measurements. The LP_{11} mode exhibited an attenuation three orders of magnitude greater than the attenuation of 0.3 dB/km for the LP_{01} mode to preclude modal dispersion. The very high attenuation in the LP_{11} mode is consistent with the n measurement. Fig. 2(a) shows that n for the LP_{11} mode is very close to n_2 indicating that the mode is barely guided.

IV. SUMMARY

Bending loss, modal noise, and spectral attenuation tests supported by guided-wave phase-index measurements show that quasi-single mode fibers are feasible for reduced bending losses in long-haul transmission in severe bending environments. Reducing bending loss by increasing the core radius to increase optical confinement of the guided wave in a quasi-single mode fiber is comparable to increasing the relative index difference in a high- Δ fiber. The feasibility of a quasi-single mode fiber for low bending loss at 1550 nm has been established, with a potential for implementation in a depressed cladding and pure-silica core to minimize Rayleigh-scattering loss.

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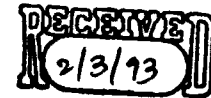
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